



## Short communication

## Research on the characteristics of the vanadium redox-flow battery in power systems applications

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## H I G H L I G H T S

- The response capability of the VRFBs is researched from the view of application.
- The maximum SOC charged by times rated power at TR = 1 is obtained.
- The minimum TR charged by times rated power at SOC = 100% is obtained.
- One threshold value and one baseline for charge/discharge demand are obtained.

## A R T I C L E I N F O

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## A B S T R A C T

Vanadium redox flow batteries (VRFBs) have power rating and energy durations that are independent of one another, which make them attractive for power systems applications. This paper focuses on the energy and power response capability of the VRFBs, which has been experimentally researched based on 5 kW/10 kWh and 0.5 MW/1 MWh systems. With three experimental operating modes, three threshold values and one baseline have been obtained based on the experimental results. The maximum state of charge ("SOC"), charged by 1.4 times rated power at 1 time ratio ("TR"), is 47% SOC. The minimum TR, charged by times rated power at SOC = 100%, is 1.5. The maximum charge/discharge power rating is 1.35 times rated power. The reserve SOC curves are a baseline on which the VRFB can respond to equally charge/discharge energy demand.

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## 1. Introduction

A confluence of industry drivers—including increased deployment of renewable generation, the high capital cost of managing grid peak demands and reliability—is creating new interest in electric energy storage systems. Energy storage systems help balance variable renewable generation sources and when properly deployed and integrated, can help increase electric grid reliability and asset utilization [1–4].

Conventional energy storage batteries often face a trade-off between the energy and power rating. The vanadium redox flow battery (VRFB), decouples the energy rating from the power rating, providing a solution to this vexing problem [5–7].

The VRFB systems typically consist of cell stacks that are constructed from several individual battery cells. The number of cells and cell stacks determine the voltage and power of the system. The

positively and negatively charged electrolyte solutions containing the redox couples are circulated through the electrodes via large capacity electrolyte storage tanks that are external to the electrochemical cell. The power output of the system increases with the size of the cell stack and the active electrode surface area, while the energy storage capacity increases with the volume of the storage tanks and the reactant concentrations. Therefore, the VRFB can be tailored to specific large-scale utility applications [8–11].

Previous work on VRFB systems has included electrode, membrane and electrolyte investigation and characterization [7,12–14]. Detailed mathematical models and system optimization have recently been developed for the VRFB [15,16]. However, greater characterization of the VRFBs with respect to different applications is needed in order to create conducive proposals and/or guidelines for the user. For example, the charge–discharge energy response capability of the VRFB in peak shaving application, and the charge–discharge power rating response capability of the VRFB in smoothing output from renewable generation sources remain relatively unexplored and poorly documented [17–20]. The

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commercially supplied VRFB systems combining experiments with some specified operating modes would be suitable for exploring these issues.

In this work, the importance of operational variables on the performance of two commercially supplied VRFB systems, 5 kW/2 kWh and 0.5 MW/1 MWh VRFB systems, is investigated. The information obtained details energy and power response capability conditions, and takes into account SOC, power rating, energy, and charge/discharge time during operation.

## 2. Experimental details

The 5 kW/10 kWh and 0.5 MW/1 MWh VRFBs experimental systems were acquired by the China Electric Power Research Institute (CEPRI) from Prudent Energy in 2010 and are installed at CEPRI laboratories in Beijing and Zhangbei respectively, as shown in Fig. 1. The 5 kW/10 kWh VRFB system is installed in a temperature controlled chamber set to 25 °C in order to provide constant experimental conditions. The 0.5 MW/1 MWh VRFB system is located in an air-conditioned workshop.

Fig. 2 shows a principle schematic of the experimental systems installed at CEPRI. In the schematic the following main components are evident: the cell stack, ancillary devices, electrolyte tanks,

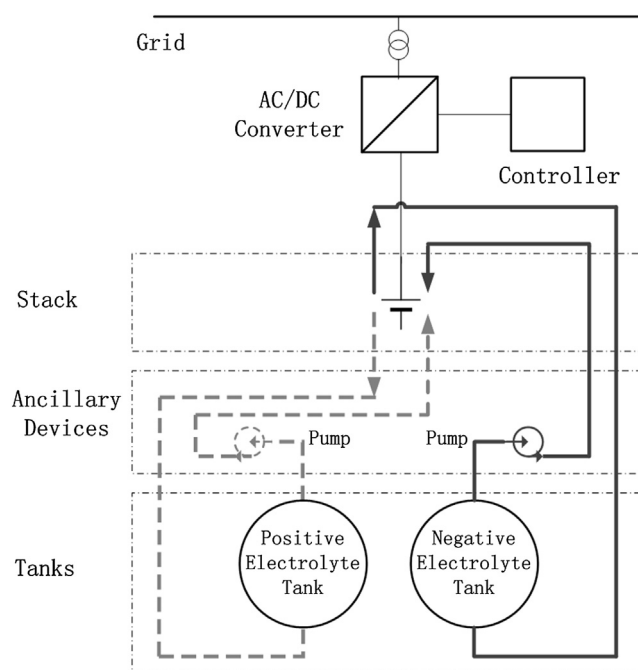


Fig. 2. Principle diagram of redox flow batteries.

controller and the AC/DC converter. The controller is the device for managing, monitoring and controlling the battery. The AC/DC converter is the necessary interface between DC battery and AC grid and its operating parameters are set through the controller. The general specifications of the two VRFB systems are listed in Table 1.

In tests, the experimental systems can operate in three modes: constant power charge-rated power discharge mode, fully charge-rated power discharge mode, and constant power charge and discharge mode. The battery is primarily managed by monitoring its SOC and voltage: 0 and 100% SOC, cell cut-off charge voltage ( $V_{\text{cell-cha}}$ ), and cell cut-off discharge voltage ( $V_{\text{cell-dis}}$ ). The three modes of operation are explained as follows:

**I Mode.** Constant power charge-rated power discharge mode: Experimental system was charged at constant power from SOC = 0% to cut-off charge voltage, and discharged at rated power to SOC = 0%.

**II Mode.** Fully charge-rated power discharge mode: Experimental system was charged at constant power/voltage from SOC = 0% to SOC = 100%, and discharged at rated power to SOC = 0%.

**III Mode.** Constant power charge/discharge mode: Experimental system was charged at constant power from SOC = 0% to cut-off charge voltage (I phase), charged at constant voltage to SOC = 100% (II phase), and then discharged at constant power from SOC = 100% to cut-off discharge voltage (III phase), and discharged at constant voltage to SOC = 0% (IV phase).

Table 1  
Rechargeable battery specifications.

Parameter	Specification	
Rated power-energy	5 kW–2 h	0.5 MW–2 h
DC voltage range	38–58.9 V	126–195 V
Number of stacks	1	72
Volume of electrolyte	0.9 m <sup>3</sup>	96 m <sup>3</sup>



Fig. 1. Appearance of two VRFB systems in CEPRI China. a: 5 kW, 2 kWh VRFB in Beijing. b: 0.5 MW, 1 MWh in Zhangbei.

Furthermore, the manufacturer has suggested a few limits due to the battery:  $P_{\text{charge/discharge}} \leq 1.5$  times rated power,  $V_{\text{cell-cha}} = 1.55$  V,  $V_{\text{cell-dis}} = 1$  V, SOC = 0–100% as an operational parameter provided by the controller.

The following equations were used to determine the efficiencies and the time ratio of the battery at the operating modes.

The energy efficiency,  $\eta_E$ , is the ratio of the time-averaged energy consumed during discharge (includes consumed energy by ancillary devices),  $E_{\text{dis}}$ , with respect to the energy consumed during charge  $E_{\text{cha}}$ :

$$\eta_E = \frac{E_{\text{dis}}}{E_{\text{cha}}} \quad (1)$$

The charge–discharge time ratio (abbreviated TR after this), is the ratio of the charge time,  $T_{\text{cha}}$ , to the discharge time,  $T_{\text{dis}}$ :

$$\text{TR} = \frac{T_{\text{cha}}}{T_{\text{dis}}} \quad (2)$$

### 3. Results and discussion

To investigate the charge–discharge energy response capability of the VRFB, I Mode and II Mode tests were performed at constant power of 0.6, 0.8, 1, 1.2 and 1.4 times rated power. The SOC, charge–discharge energy and times were obtained for each mode.

The SOC profiles for the I and II Modes at constant power rating and the corresponding TR profiles are illustrated in Fig. 3. The differences of SOC between the modes increased gradually, while the TR of both modes decreased gradually when the charge power rating increased. The maximum difference of SOC is 55.3% at 1.4 times rated power. The TR of I and II Modes decreased from 2.98 to 1.18 and 1.54 respectively, indicating that the 1.4 times rated power provides a significantly superior TR. Two threshold values for response to energy demand, the maximum SOC charged by times rated power at TR = 1 and the minimum TR charged by times rated power at SOC = 100%, can be obtained. The maximum SOC, charged by times rated power at TR = 1, is 47% SOC, meaning the energy charged by 1.4 times rated power for a certain time, can be discharged by the rated power for the same time, but the maximum energy charged is only 47% of the rated energy. The minimum TR, charged by times rated power at SOC = 100%, is 1.5, meaning the 100% SOC, fully charged by 1.4 times rated power and constant voltage at 3 h, can be discharged to 0% SOC by rated power at 2 h.

Fig. 4 shows the energy efficiencies and SOC according to the charge power rating in I Mode and II Mode. In both the modes, the

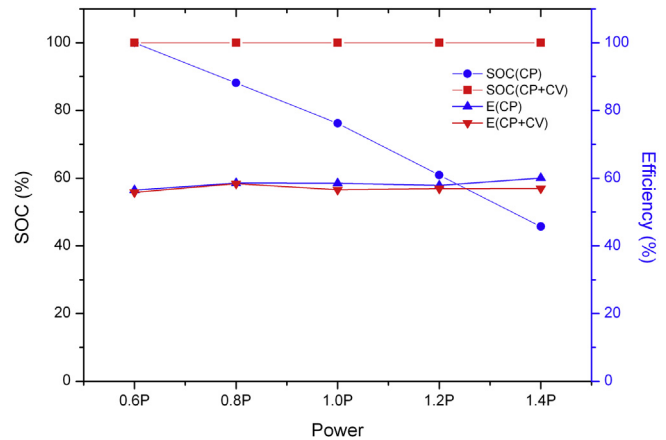


Fig. 4. Efficiencies and SOC according to the charge power rating.

energy efficiency is almost constant. When the charge power rating increases to 1.4 times rated power the energy efficiency increases slightly from 56.5% to 60% in case of I Mode, while the efficiency increases slightly from 55.8% to 56.9% in case of II Mode. The maximum difference of efficiency between the modes is only 3% at 1.4 times rated power, but the maximum difference of SOC is 55.3%. This shows that the energy efficiency of the experimental systems is insensitive to the differences charge power rating and energy amount in both operations modes. The higher power can effectively improve the response ability of the energy demand; however, the reliability and safety analysis of VRFBs needs further study for long-term operation.

To investigate the charge–discharge power rating response capability of the VRFB, III Mode characterization was performed at constant power of 0.6, 0.8, 1, 1.2 and 1.4 times rated power. The SOC, charge–discharge voltage and power rating were obtained. In Fig. 5, the left-hand curves are the discharge SOC curves in III phase, and the right-hand curves are charge curves in I phase.

In Fig. 6, with the power rating on the horizontal axis and the SOC on the vertical axis, the maximum boundary curves of the charge SOC and the minimum boundary curves of discharge SOC are obtained respectively by the charge–discharge cutoff SOC from Fig. 5. One threshold value and one baseline, the maximum charge/discharge power rating and reserve SOC for responding equally to charge/discharge energy demand, can be obtained. With the

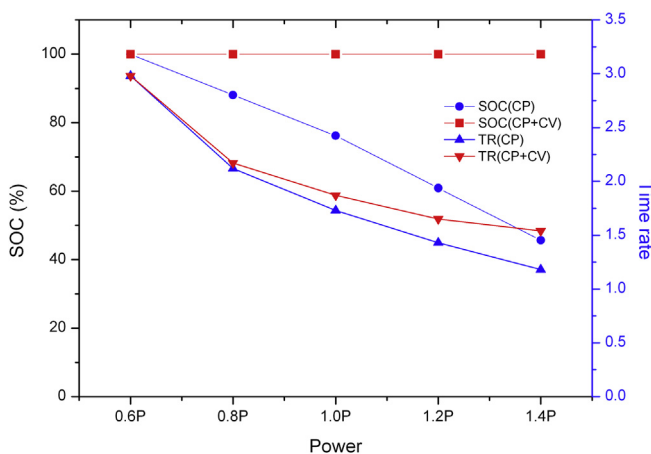


Fig. 3. TR and SOC according to the charge power rating.

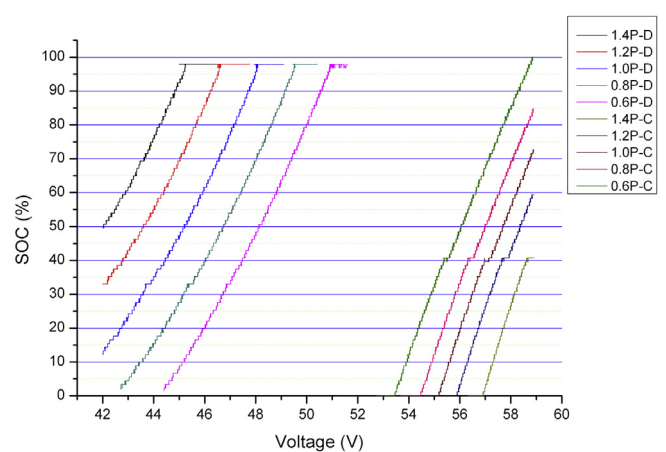


Fig. 5. VRFB charge–discharge curves according to the charge power rating.

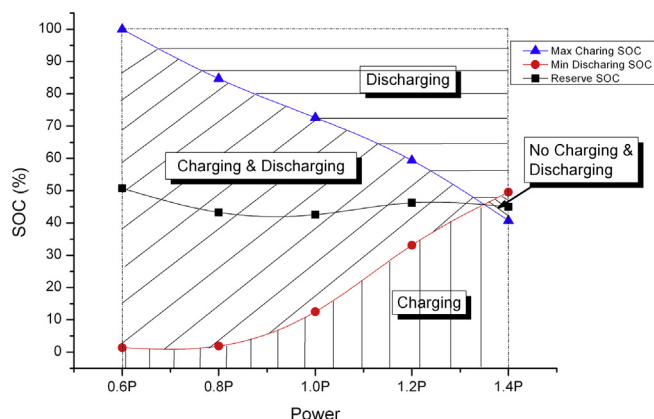


Fig. 6. VRFB ability to respond to charge/discharge power rating demands.

Table 2

The symmetric charge/discharge energy at each power level.

Discharge/charge power (Rated Power)	Max charge SOC (%)	Min discharge SOC (%)	Reserve SOC (%)	Symmetric charge/discharge SOC (%)
0.6	100	0	50.0	$\pm 50.0$
0.8	84.7	1.9	43.3	$\pm 41.4$
1.0	72.6	12.5	42.6	$\pm 30.1$
1.2	59.4	33.1	46.3	$\pm 13.1$
1.4	40.7	49.5	—	—

discharge/charge power rating increasing, both curves converge and intersect at 1.35 times rated power.

Four areas, (1) charging, (2) discharging, (3) charging & discharging, and (4) no charging & discharging, are divided by the two curves in Fig. 6. Under the charge–discharge power response capability consideration, these four areas are explained as follows:

- (1) Charging areas: the VRFB system can only be charged at 0.6–1.4 times rated power.
- (2) Discharging areas: the VRFB system can only be discharged at 0.6–1.4 times rated power.
- (3) Charging & discharging areas: the VRFB systems can be either charged or discharged at 0.6–1.35 times rated power.
- (4) No charging & discharging areas: the VRFB can be neither charged nor discharged at or above 1.35 times rated power.

The maximum charge/discharge power rating of the experimental systems is 1.35 times rated power.

On the Reserve SOC curve in Fig. 6, VRFB has both the ability to respond to charge/discharge power rating and symmetric charge/discharge energy. Table 2 indicates the symmetric charge/discharge energy at each power rating level. The 50% SOC VRFB systems can output  $\pm 50\%$  symmetric charge/discharge energy at 0.6 times rated power. The symmetric charge/discharge energy ranges gradually decrease, when the charge/discharge power rating increases. The 46% SOC VRFB systems can only output  $\pm 13.1\%$  symmetric charge/discharge energy at 1.2 times rated power. The reserve SOC curves are a baseline on which the VRFB can respond to equally charge/discharge energy demand.

#### 4. Conclusions

The energy and power response capability of VRFB has been experimentally investigated, using two commercially available

systems of 5 kW/10 kWh and 0.5 MW/1 MWh. By constant power charge-rated power discharge mode and fully charge-rated power discharge mode, two threshold values of the VRFB for respond to energy demand have been obtained. The maximum SOC, charged by times rated power at  $TR = 1$ , is 47% SOC. The minimum TR, charged by times rated power at  $SOC = 100\%$ , is 1.5. By The constant power charge/discharge mode, one threshold value and one baseline of the VRFB for respond to power rating demand have been obtained. The maximum charge/discharge power rating is 1.35 times rated power. The Reserve SOC curve is a baseline from which the VRFB can respond equally to charge/discharge energy demand.

Though there are different threshold values depending on the VRFB manufacturer and system configuration, this paper provides experimental support and analysis methodology for configuring the system energy and power capacity, determining the work to be performed, and developing operating strategies for the application. The experimental results and analytical methods can also provide a reference for other energy storage battery application analyses.

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